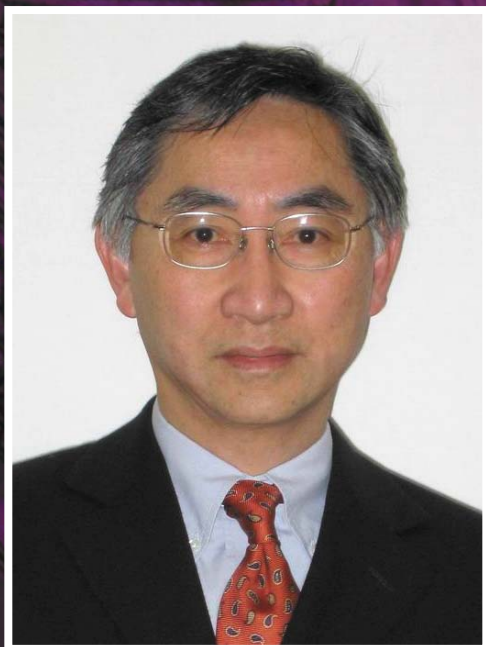


# 3.2.1.4.2

## Low Swirl Combustion



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### 3.2.1.4.2-1 Introduction

Lean-premixed (LP) combustion technologies have been adopted by virtually every industrial gas turbine manufacturer as a Dry Low  $\text{NO}_x$  (DLN) method to meet emissions regulations which are being implemented in the US and in many regions worldwide. But to meet more stringent ultra-low emissions standards being proposed, the DLN combustors have to operate at conditions near the lean limit of their stability envelopes where noise, instability, flame blowoff, and flashback can seriously affect engine performance. To mitigate these potential problems much effort has been devoted to explore passive control, e.g., fuel and/or air staging, and active control, e.g., feedback loop, strategies. Other alternatives invoke more costly exhaust gas clean up or catalytically assisted combustion. Undoubtedly, utilization of these new schemes would lead to more complex combustion devices consisting of tightly controlled sensors and actuators as well as many auxiliary components. For coal-based syngas engines the instability problems are further exacerbated due to the variability of the fuel contents. Therefore the injectors as well as the combustors have to be optimized or re-engineered to accommodate the changes in the combustion properties. Because most turbine combustors are designed for natural gas, they may not be readily adaptable or scalable to burn IGCC fuels.

One promising solution to resolve fuel flexibility issues of IGCC turbines is a novel premixed combustion technology that operates on a unique low-swirl combustion (LSC) concept. Originally developed at the Lawrence Berkeley National Laboratory as a small laboratory research burner (about 15 kW) for fundamental studies, a good understanding of its operating principle has been obtained<sup>1</sup>. This patented combustion concept is based on exploiting the aerodynamic properties of the propagating premixed flames<sup>2</sup>. It is a simple, robust, and readily adaptable technology for industrial process burners and gas turbine combustors to meet stringent emissions targets without significantly altering their system configurations, efficiencies, turndown, and costs. LSC has been commercialized for industrial process heaters as low-swirl burners (LSB). Products of 150 kW to 7.5 MW (0.5 to 25 MMBtu/hr) with ultra-low emissions of 4 – 7 ppm  $\text{NO}_x$  and CO (both @3%  $\text{O}_2$ ) have been available since late 2003. Central to the commercialization pathway was the scientific knowledge obtained from laboratory studies that has provided critical information for scaling as well as resolving system integration issues. LSC is also being adapted for natural gas turbines. Rig tests of prototype low-swirl injectors (LSI) for 10 MW size engines show it to be a very promising and cost-effective solution as “plug-in” injector replacements to enable current DLN turbines to meet the emission targets of < 5 ppm (@ 15%  $\text{O}_2$ ) for both  $\text{NO}_x$  and CO.

The LSC concept is readily adaptable for burning other hydrocarbons and hydrogen enriched fuels. Its operating principle is based on matching the flowfield to the turbulent premixed flame speeds of ultra-lean premixed flames. Laboratory measurements of flame speeds and flame temperatures for the alternate fuels will be necessary to obtain basic information for optimizing the LSC design. This strategy has already been applied to develop fuel-flexible industrial LSBs. Prototypes have been tested with propane, ethylene, natural gas diluted with flue gases (up to 40%), and refinery gases with large hydrogen constituencies (up to 50%  $\text{H}_2$ ). The main technical issue for adapting LSI to IGCC syngas turbines concerns the significantly different combustion properties of the two principal types of gasified coal fuels. Typical compositions of the syngas from oxygen blown coal gasification are 25%  $\text{H}_2$ , 40% CO, 20%  $\text{H}_2\text{O}$ , with a lower heating value of 200 BTU/ft<sup>3</sup>. With the addition of  $\text{CO}_2$  separation and sequestration, the syngas composition shifts to mostly hydrogen at 65-85%  $\text{H}_2$ , and 15-35%  $\text{H}_2\text{O}$ . These syngases have diverse combustion properties and the LSI needs to be optimized for the slower and faster burning flames (compared to natural gas) at operating conditions where the flame temperatures are sufficiently low to prevent  $\text{NO}_x$  formation. Other concerns stem from the high  $\text{H}_2$  diffusivity and short auto-ignition delay time. Therefore, issues on system integration will need to address the impact on flashback, blow-off, light-off, shut-down, off-load, and load following. Currently, the research activities have been limited to proof-of-concept laboratory experiments using hydrogen and hydrogen/hydrocarbon blended fuels. More extensive laboratory studies will be necessary to develop basic LSI designs optimized for syngases and the accompanying scaling rules and engineering guidelines.

### 3.2.1.4.2-2 Principle of Low-swirl Combustion and Technology Transfer History

Swirling flow burners have been essential to both premixed and non-premixed combustion systems because of their significant beneficial influences on flame stability, and combustion intensity, as well as the combustor performance. Until now, gas turbine combustors and industrial systems utilized a high-swirl type of burner in which the swirling motion generated by the injector (or burner) is sufficiently high to produce a fully developed internal recirculation zone at the entrance of the combustor. For conventional non-premixed combustion, the role of the large recirculation zone, also known as the toroidal vortex core, is to promote turbulent mixing of the fuel and air. In premixed DLN systems, the recirculation zone provides a stable heat source for continuous ignition of the fresh reactants. Refer to the review of Syred and Beer for extensive background on the basic processes and practical implementation of high-swirl combustors<sup>3</sup>.

Low-swirl combustion is a relatively recent development. It is an excellent tool for laboratory research on flame/turbulent interactions<sup>4</sup>. Its operating principle exploits the “propagating wave” nature of premixed flames and is not valid for non-premixed combustion. Premixed flames consume the reactants in the form of self-sustained reacting waves that propagate at flame speeds controlled by the mixture compositions, the thermodynamic conditions, and turbulence intensities. In contrast, non-premixed diffusion flames do not propagate (i.e., move through the reactants) because burning occurs only at the mixing zones of the fuel and oxidizer streams. To capture a fast moving turbulent premixed flame as a “standing wave” that remains stationary, low-swirl combustion exploits a fluid mechanical phenomenon called a divergent flow. As the name implies, divergent flow is an expanding flow stream. It is formed when the swirl intensities are deliberately low such that vortex breakdown, a precursor to the formation of flow reversal and recirculation, does not occur. Therefore, the LSC principle is fundamentally different from the high-swirl concept of typical DLN gas turbines where strong toroidal vortices are the essential flow elements to hold and continuously re-ignite the flames.

The original LSB for laboratory studies known as the jet-LSB is shown in figure 1<sup>5</sup>. This burner is essentially a cylindrical tube of 5.08 cm diameter fitted with a tangential air swirler section consisting of four small inclined jets of 0.63 cm in diameter. Reactants at a given fuel air equivalence ratio is supplied to the bottom of the tube. After passing through a turbulence generating plate, the reactants stream interacts with the tangential flow supplied through the jets. The size of the air-jets is kept small so that the swirling motions cling to the inner wall of the burner tube and do not penetrate into the center. When the flow exits the burner, centrifugal force due to the swirling motions causes the flow to expand and diverge. This divergent flow has a non-swirling core surrounded by a swirling shroud that weakens progressively downstream. Within the non-swirling center core, the adverse mean axial pressure gradient is accompanied by a linear decrease in the mean axial velocity. This velocity “down ramp” provides a very stable flow configuration for a premixed turbulent flame to freely propagate and settle at a position where the local flow velocity is equal and opposite to the flame speed. The flame does not flashback into the burner because it cannot propagate faster than the velocity at the burner exit. Blow off is also mitigated because the center non-swirling core provides a broad region where the flame naturally settles. More importantly, over mixture inhomogeneity or slight flow transients cause only a shift in the flame position so that the likelihood of catastrophic flameout is minimized. This is a robust self-adjusting mechanism for the flame to withstand transients and changes in mixture and flow conditions.

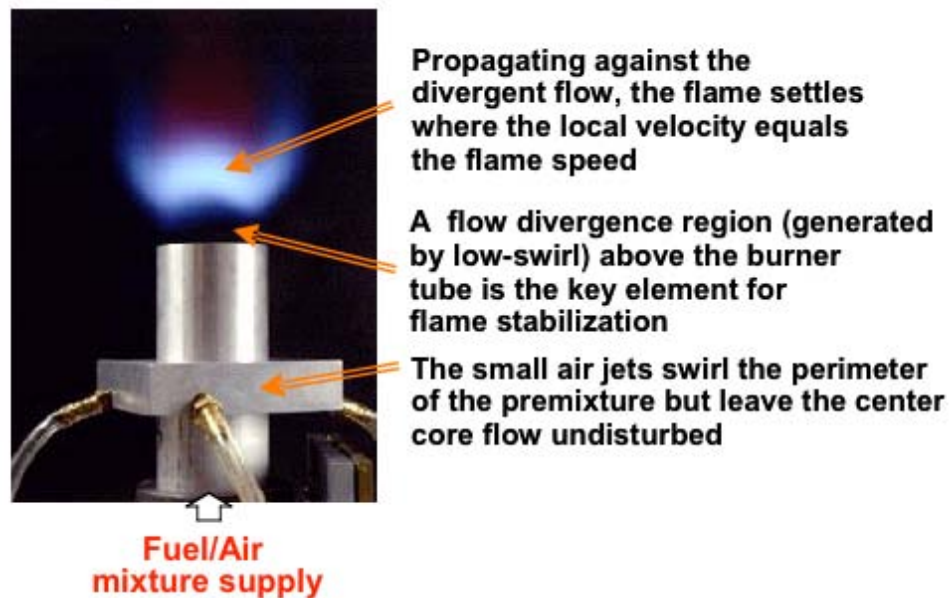


Fig. 1. A jet-LSB demonstrates the principle of low-swirl flame stabilization.

The flow feature crucial to flame stabilization is illustrated by the axial velocity profiles. Plotted in figure 2 are measurements obtained by laser Doppler velocimetry (LDV) published in Yegian and Cheng's article where the effects of enclosure were evaluated by placing the jet-LSB inside quartz cylinders of 7.62 cm diameter, 20 and 30 cm in length with or without an exit constriction of 5.4 cm diameter to simulate typical combustor enclosures<sup>6</sup>. The experimental conditions were CH<sub>4</sub>/air flames with  $\phi = 0.8$  and 18.5 kW corresponding to a bulk flow velocity of  $U_0 = 3.0$  m/s. From the mean axial velocity ( $u$ ) profiles (top), it can be seen that the velocity at the burner exit is slightly lower than  $U_0$  (about 70%). In the region just outside the exit ( $x < 20$  mm), a linear decaying trend (with increasing  $x$ ) shown on all the  $U/U_0$  profiles is the characteristic feature of flow divergence. The leading edge of the flame brushes are marked by the abrupt upturn in the profiles at  $20 < x < 40$  mm. These increases are due to combustion-generated flow acceleration. The minimum velocity on the  $U/U_0$  profiles corresponds to the velocity normal to the leading edge of the turbulent flame brushes and offers a convenient means to determine the turbulent flame speed,  $S_T$ . Studies of  $S_T$  using the jet-LSB show that a linear correlation exists between  $S_T$  and turbulence intensity over a very broad range of turbulence intensities<sup>7</sup>. This is an important property that enables the LSC concept to be scaled to the capacities of very large industrial combustion systems.

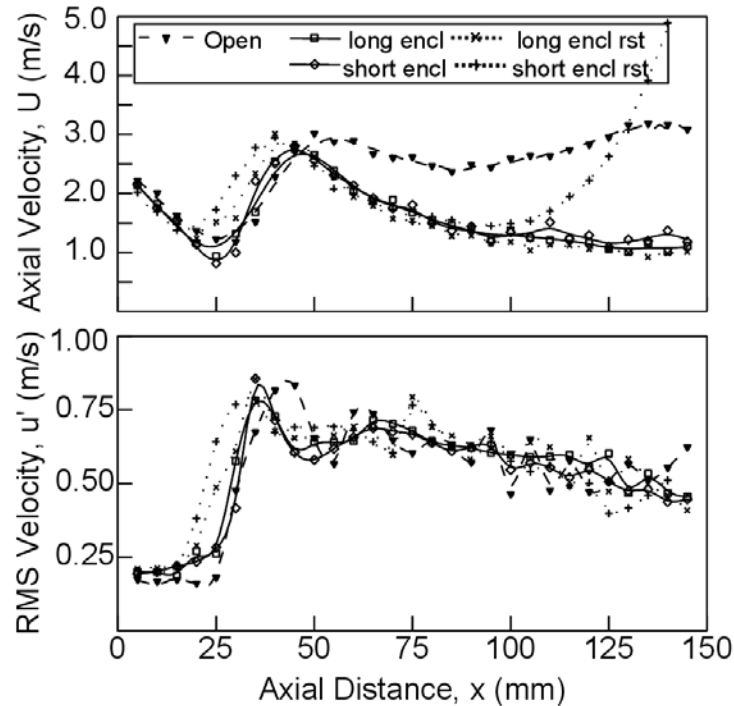


Fig. 2. Velocity profile showing that enclosures have little effect on the flame stabilization mechanism of a jet-LSB with CH<sub>4</sub>/air flame of  $\phi = 0.8$  at 18.5 kW (reproduced with permission from *Combustion Science and Technology*).

Source: D.T. Yegian and R.K. Cheng, "Development of a Lean Premixed Low-Swirl Burner for Low NO<sub>x</sub> Practical Applications," *Combustion Science and Technology* 139 no. 1-6 (1998): 207-227.

Technology transfer of LSC began with adaptation to residential pool heaters of 15 to 90 kW (50 to 300 KBtu/hr). These small domestic heaters are consumer products. To be price competitive they can only accept very simple and low-cost technologies that utilize rudimentary electronic controls. A LSB that has separate control for swirl jets and combustion air was deemed too elaborate to be economically and practically feasible. Therefore the key task was to develop a simpler burner that is easy to manufacture and requires few controls. The outcome of this work was a patented vane-swirler that has since been adapted for gas turbines.

The main challenge in the swirler development process was a lack of relevant background knowledge on low-swirl flows. All prior research efforts on swirl combustion emphasized the generation of strong and stable flow recirculation. Extensive laboratory experimentation by LDV led to the design of figure 3. This LSB was sized for domestic heaters of 18 KW with a radius  $R_b$  of 2.54 cm. The unique feature of the swirler is a center by-pass channel ( $R_c = 2$  cm) to allow a portion of the reactants to pass without being swirled by the outer annulus swirl vane section fitted with eight straight blades inclined at an angle  $\alpha$  of 37.5°. The novelty of this design is the use of a perforated screen to control the flow-split between the unswirled core and the swirled annulus. The screen also produces turbulence in the center unswirled core. Because turbulence scales with flow velocity, it provides a crucial feedback control mechanism for the flame to accelerate and decelerate in response to changes in bulk flow, i.e. load change. The perforated screen fitted to the LSB in figure 3 has 3 mm holes arranged in a rectangular grid to give 81% blockage. By recessing this swirler assembly inside the burner tube at a distance,  $L$ , this burner produces the key flowfield features same as the jet-LSB.



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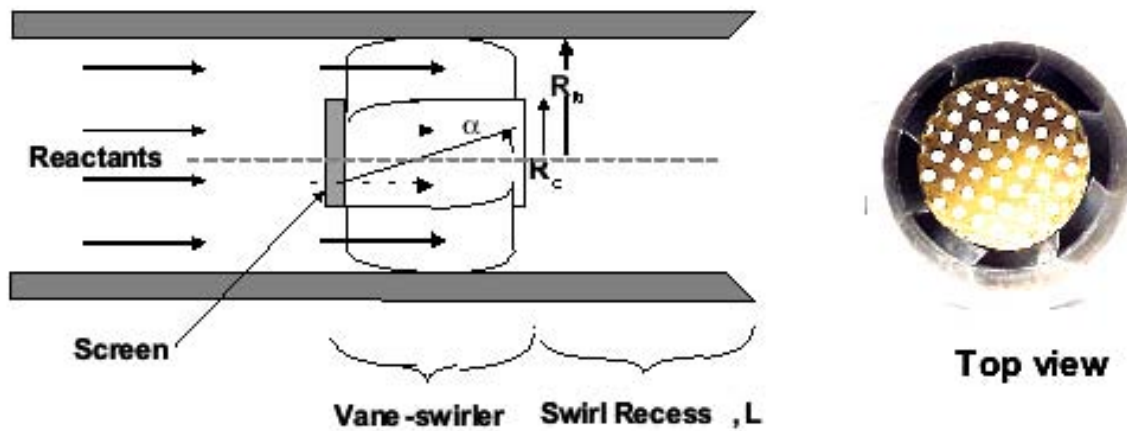


Fig. 3. Schematics of a vane swirler developed for the low swirl burner.

As shown in figure 4, the flame generated by the LSB is lifted with a bowl shape slightly different than the one produced by a jet-LSB. To demonstrate an exceptional feature of the LSC concept, all the components of the LSB in figure 3 were made of plastic to show that it does not receive significant heat from the flame. This has important practical significance because the burner suffers little or no material degradation due to a substantial reduction in thermal stresses.

Subsequent to the development for pool heaters, several projects have been pursued to adapt LSB to industrial and commercial heaters. The efforts began by conducting parametric studies of LSB by varying  $R_b$  (2.54, 3.8, 5.1 and 6.35 cm),  $R_c$  ( $0.5 < R_c/R_b < 0.8$ ),  $\alpha$  ( $37^\circ$  to  $45^\circ$ ), and  $L$  ( $1 < L/R_b < 4$ ). Also investigated were other geometric variations such as the number of vanes, vane types (i.e., straight and aerodynamically shaped), types of center screens and their placement positions. The laboratory experiments and field tests were all performed with natural gas. The scientific foundation obtained for LSC has been most valuable to support data analyses and to devise solutions that meet specific operational and performance requirements.

These studies proved that the LSB design is robust. To investigate turndown, the smallest LSB with  $R_b = 2.54$  cm was fired in the open and generated stable flames from 10 to 600 kW that remained stationary despite the 60 to 1 change in input rate. At the lowest thermal input of 10 kW, the bulk flow velocity  $U_0$  corresponds to 1.7 m/s. This is the minimum allowable operating point for natural gas firing. Flashback becomes likely if  $U_0$  were reduced further because the velocity at the burner exit would be too close to the  $S_T$ . The minimum  $U_0$  criterion to avoid flashback applies unequivocally to the larger burners because the LSB subscribes to constant velocity scaling. This simply means that the thermal input of LSB is directly proportional to  $U_0$  and  $R_b^2$ . The effects of enclosure geometry on LSB performances was also investigated by testing several versions of the  $R_b = 6.35$  cm LSB in boilers and furnaces at 150 kW to 2.3 MW. The results showed that vane shape and screen placement had little effect on flame noise, flame stability, and lean blow off. Most significantly, emissions of  $NO_x$  depend primarily on  $\phi$ . As shown in figure 5 by the  $NO_x$  emissions from LSB of various sizes, the trends with  $\phi$  are similar despite differences in thermal inputs and combustor geometries to show its capability to accept different fuels. Additional tests of the 6.35 cm LSB were performed with alternate fuels including natural gas diluted with up to 40% flue gases and refinery gases with hydrogen constituent up to 50%.



Fig. 4. A vane-LSB firing at 18kW.

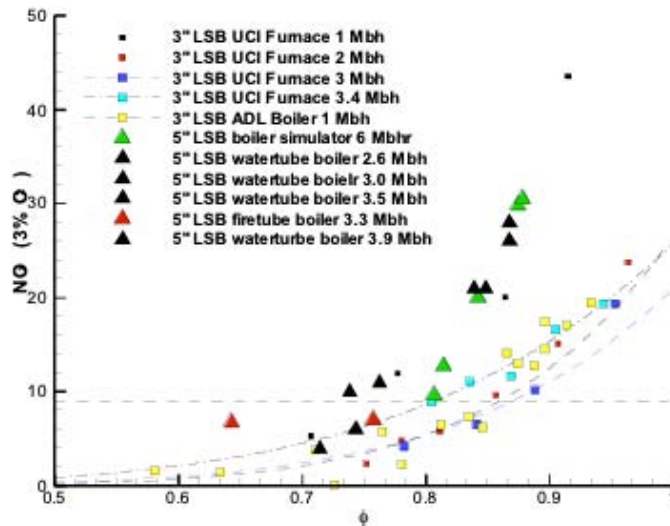


Fig 5. NO<sub>x</sub> emissions of LSB in furnaces and boilers of 300 kW to 1.8 MW.

In 2003, Maxon Corporation commercialized a line of industrial LSBs called M-PAKT burners. These products are developed for direct process heat applications of 0.3 to 1.8 MW (1- 6 MMBtu/hr) with a guarantee of 4 – 7 ppm NO<sub>x</sub> and CO (both at 3% O<sub>2</sub>) throughout its 10:1 turndown range. With these ultra-low emissions, the M-PAKT burners meet the most stringent air-quality rules in the U.S. As shown by the schematic in figure 6, the M-PAKT burner has a very simple compact design consisting of the swirler with air supplied by a blower through a plenum and a multi-port natural gas injector delivering fuel just upstream of the swirler. The control system is standard with conventional mechanical linkages and flow dampers. The exceptional performance of these commercial LSBs demonstrates that the implementation of LSC not only provides very effective emissions control but also improves system performance and reliability by eliminating the need for elaborate controls and intricate auxiliary components. The economic and operational benefit of this approach cannot be understated. In their continuing effort to commercialize LSC technology, Maxon engineers applied the scaling rules described in the next section to design a new LSB product of 7.5 MW (25 MMBtu/hr). The first installation was complete in February 2005. This large burner has a radius  $R_b$  of 25.4 cm and has an improved 20:1 turndown. It also incorporates a liquid fuel injector for dual-fuel firing.

### 3.2.1.4.2-3 Scaling rules and engineering guidelines

The current size range of LSB from the smallest laboratory 7 kW unit of  $R_b = 1.27$  cm to the largest 7.5 MW industrial burner represents a scaling factor of over 1000. This has been accomplished by using a set of scaling rules for the geometric variables and engineering guidelines for the LSBs to meet system integration and operational requirements. These design rules and guidelines are the significant outcomes of the technology development efforts. They represent the synthesis of the knowledge gained from extensive laboratory experiments and analyses based on theories on flame temperature, flame speeds, and reaction chemistry as well as combustion aerodynamics, turbulence, and turbulence/flame interactions. Though these rules and guidelines have been developed for natural gas, similar guidelines can be obtained for other fuels to account for the resulting changes in combustion properties.

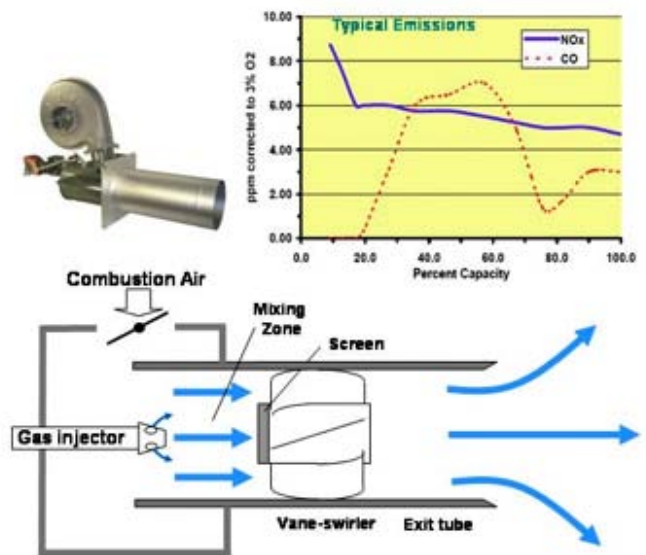


Fig. 6. Emissions and schematic of a commercial LSB manufactured by Maxon Corporation, Muncie, Indiana.

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Central to the scaling rule is the definition of a swirl number,  $S$ , for the LSB. It is derived from the formal definition of  $S$  based on the ratio of angular to axial flow momentum<sup>8</sup>:

$$S = \frac{G_{ang}}{R_b G'_x} = \frac{\int_0^{\infty} \rho U W r^2 dr}{R_b \int_0^{\infty} \rho \left( U^2 - \frac{1}{2} W^2 \right) r dr} \quad (1)$$

where  $G_{ang}$  is the angular momentum in the swirled section and  $G'_x$  is the linear momentum flux through the unswirled center core and the swirled annulus. These terms can be calculated by integrating the mean axial,  $U$ , and the mean swirl,  $W$ , velocity components across the burner exit. However, this definition is not convenient because velocity data are not usually available. For engineering applications, a swirl number definition based on the geometry of the device is more amenable. With the assumption that the distribution of the axial flow remains flat, and  $U$  and  $W$  at the burner exit are kinematically related to the blade angle as  $\tan \alpha = U/W$ , the axial flux of angular momentum in the annular section is then written as follows:

$$G_{ang} = 2\pi\rho \int_{R_c}^{R_b} U_a (U_a \tan \alpha) r^2 dr = 2\pi\rho U_a^2 \tan \alpha \left( \frac{R_b^3 - R_c^3}{3} \right) \quad (2)$$

Here,  $U_a$  is a mean axial velocity supplied through the swirl annulus. By assuming flat axial velocity distribution, the linear momentum flux from the two regions of the burner is then calculated as follows:

$$G_x = 2\pi\rho \int_{R_c}^{R_b} U_a^2 r dr + 2\pi\rho \int_0^{R_c} U_c^2 r dr = \pi \left[ \rho U_a^2 (R_b^2 - R_c^2) + \rho U_c^2 R_c^2 \right] \quad (3)$$

where  $U_c$  is a mean axial velocity through the center core. With Equation (1) as defined, the geometric swirl number for the vane swirl burner is then:

$$S = \frac{\frac{2}{3} \tan \alpha (1 - R^3)}{\left( 1 - R^2 + \frac{U_c^2}{U_a^2} R^2 \right)} = \frac{2}{3} \tan \alpha \frac{1 - R^3}{1 - R^2 + [m^2 (1/R^2 - 1)] R^2} \quad (4)$$

Here,  $R$  is the ratio of centerbody to burner radii  $R = R_c / R_b$ . It is simplified further when  $U_c/U_a$  is expressed in terms of  $m$  the mass flux ratio (flow-split)  $m = \dot{m}_c / \dot{m}_a$  through the centerbody ( $\dot{m}_c$ ) and annular ( $\dot{m}_a$ ). The mass flux ratio is the same as the ratio of the effective areas of the center core and the swirl annulus and can be determined simply by the use of standard flow pressure drop procedure. Obviously, it is a more convenient form for engineering designs.

The scaling rules were deduced from studying the influences of varying  $S$ ,  $L$  and  $R_b$  on the burner operation. To start, the LSB prototype of figure 2 was used as a benchmark with its swirl number varied by the use of four different screens with 65 to 75% blockage. The swirl numbers were  $0.4 < S < 0.44$  corresponding to  $m$  of 0.8 to 1 meaning that 44 to 50% of the reactants bypassed the swirl annulus. These swirlers installed with  $L$  varied from 4 to 12 cm. The 16 LSBs with various combinations were tested with methane air flames at  $5 < U_0 < 25$  m/s covering a thermal input range of 18 to 90 kW. All burners were found to be operable. Increasing  $S$  pulled the flame closer to the burner but the lean blowoff (LBO) remained relatively unaffected indicating that the performance of the LSB is not highly sensitive to a small variation in  $S$ . The differences were mainly with flame positions and the fuel/air equivalence ratio at lean blowoff,  $\phi_{LBO}$ . Large swirler recesses generated a highly lifted flame but the overall flame stability remained relatively unchanged. A short recess distance produces higher  $\phi_{LBO}$  indicating a compromise in the capability to support ultra-lean flames.

Additional studies were performed to explore the impact of radius  $R_b$  as well as  $R$  (0.5 to 0.8) and  $\alpha$  ( $30^\circ$  to  $45^\circ$ ). The swirl numbers of the burners with various combinations of  $R_b$ ,  $R$  and  $\alpha$  were varied by fitting them with screens of different blockages. The most significant finding was that the LSBs with larger diameters  $R_b$  operate at the same range of  $S$  (around 0.4 to 0.5) as the smaller burner. Their performances in terms of flame stability and  $\phi_{LBO}$  were also identical. Moreover, decreasing  $R$  has no effects on emissions or performance but brings about a significant benefit in lowering the pressure drop of the LSB. This can be explained by the fact that reducing  $R$  enlarges the swirl annulus and lowers its drag. To maintain a swirl number of 0.4 to 0.5, a screen of lower blockage is required. For example, the screen used for the  $R_b = 6.35$  cm with  $R = 0.5$  has a 60% blockage compared to 65 to 81% needed for the  $R = 0.8$  LSB. This combination effectively lowers the overall pressure drop of the burner. The drag coefficients determined for the different LSBs show them to depend only on  $R$  and independent of  $R_b$ . This knowledge is very important in the design of LSBs that will meet the various system requirements and efficiency targets.

The scaling rules for the LSB were established from these results. They are the same regardless of burner radius (up to  $R_b = 25.4$  cm). For stable and reliable operation,  $S$  of a LSB should be between 0.4 and 0.55. The swirler can have straight or curved vanes with angle  $\alpha$  from 37 to 45°. The optimum center channel to burner radius ratios  $R$  can be from 0.5 to 0.8. Once  $\alpha$  and  $R$  are defined, the blockage of the center channel screen can be varied to set  $S$  within the range of 0.4 to 0.5. In addition,  $L$  can be from 2 to 3 times the burner radius  $R_b$ . To determine the appropriate burner size,  $R_b$ , guidelines have been developed to optimize for the desired thermal input range, turndown, fuel pressure, fan power (pressure drop), combustion chamber size, and other physical constraints. The criterion for minimum thermal input is a bulk flow velocity of  $U_0 = 3$  m/s. This is simply the flashback point for natural gas ( $U_0 \approx 1.7$  m/s) with a built-in safety factor. There is no restriction on the maximum thermal input owing to the high turndown (at least 20) available. To optimize for the fuel pressure and fan power, the drag coefficient for different  $R$  can be used. The optimum enclosure radius for the LSB is between 3 to 4 times  $R_b$ . Smaller enclosures restrict flow divergence and forces the flame to move inside the burner. Larger enclosures allow the flame to over-expand and generate internal flow patterns that negatively affect emissions. These rules and guidelines are easy to apply and are versatile enough to provide many design options to build simple and low cost LSBs for easy integration to existing or new systems.

### 3.2.1.4.2-4 Flowfield characteristics and their relevance to flame stability

Low-swirl combustion exploits combustion aerodynamics. Understanding the flowfield characteristics of LSB and how these characteristics affect flame properties is central to the future development of the technology for IGCC turbines. Laboratory experiments remain an important step to provide an understanding of the underlying mechanisms that enable LSB to maintain its performance over a large range of conditions. The advent of Particle Image Velocimetry (PIV) has greatly facilitated the characterization of the LSB flowfields. In a recent investigation, a series of experiments were conducted to investigate the evolution of flow and flame features with increasing  $U_0$ . PIV captures in 2D the velocity distributions in a relatively large region. Our system was configured to have a 13 x 13 cm field-of-view covering the entire flame region of the laboratory burners. Shown in figure 7 is an example of the velocity vectors and turbulence stresses for a LSB with  $S = 0.53$ ,  $R_b = 2.54$  cm,  $R = 0.5$ ,  $\alpha = 37^\circ$  and  $L = 6.3$  cm burning a methane/air flame of  $\phi = 0.8$  and  $U_0 = 5.0$  m/s. The leading edge of the flame brush is outlined by the broken line. These velocity vectors show that the LSB flowfield is relatively uniform and free of steep velocity gradients. The background contours of the positive (red) and negative (blue) shear stresses also show that high turbulence stresses are relegated to the outer edges where the reactants mix with the room air. The center flow entering the flame brush is in fact relatively free of large shear stresses. The absence of high stresses means that the flames are much less vulnerable to stress induced non-uniform heat release and local quenching at ultra-lean conditions. This feature is very unlike those in other burners where steep velocity gradients are found at the flame stabilization region and the shear stresses can lead to premature flame blowoff.

The evolution of the flowfield with  $U_0$  was investigated by applying PIV at  $5 < U_0 < 17.5$  m/s. Shown in figure 8 are the normalized axial velocity profiles from the non-reacting cases. The fact that the profiles of the normalized axial velocity,  $U/U_0$ , and the normalized two-component turbulent kinetic energy,  $q'/U_0$  ( $q' = ((u'^2 + v'^2)/2)^{1/2}$ ) collapse to their respective trends shows that the LSB flowfield exhibits similarity feature. Similarity is also shown by radial profiles of  $U/U_0$  and  $V/U_0$  meaning that the key flowfield features are preserved at different bulk flow velocities.

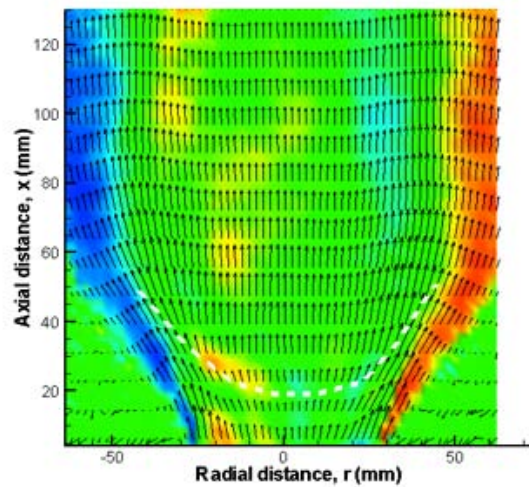


Fig. 7. Velocity vectors and shear stresses (background contours) obtained in  $R_b = 2.54$  cm LSB with methane air flame of  $\phi = 0.8$  and  $U_0 = 5$  m/s. White dash line marks the leading edge of the flame brush.



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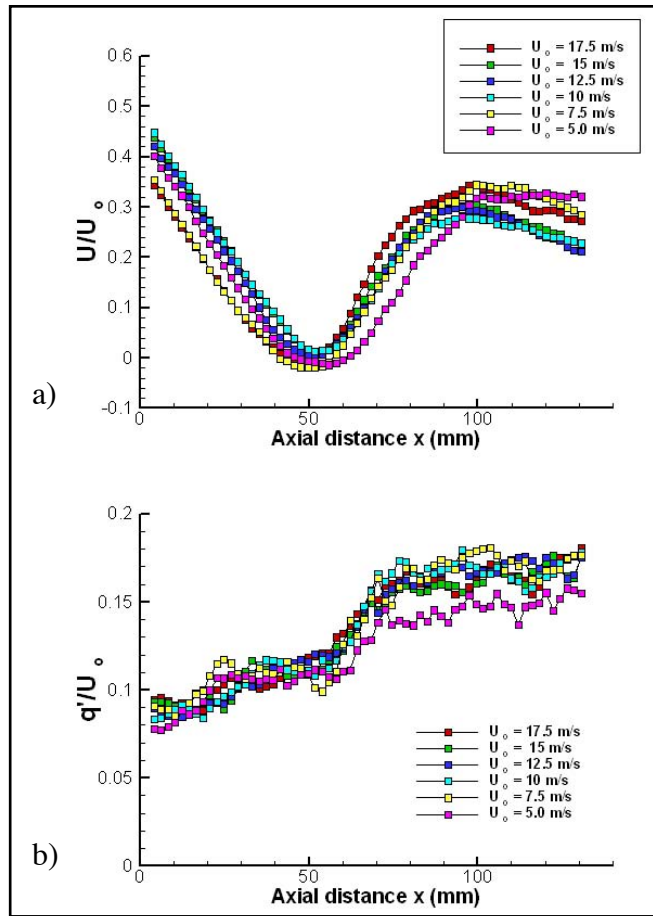


Fig. 8. Normalized centerline profiles of non-reacting flow produced by a laboratory LSB showing self-similarity features.

Flowfield similarity explains why the flame maintains at a relatively fixed position regardless of  $U_o$ . This can be illustrated by invoking an equality at the leading edge position of the flame brush,  $x_f$  (typically at  $1.5 < x < 2.5$  cm for this LSB).

$$U_o - \frac{dU}{dx} (x_f - x_o) = S_T \quad (5)$$

Here,  $x_o$  is the virtual origin of the linearly divergent portions of the axial profiles and has a negative value. As discussed earlier,  $S_T$  of the LSB is linearly dependent on the rms velocity of the turbulence  $u'$  such that  $S_T = S_L (1 + K u')$  where  $S_L$  is the laminar flame speed and  $K$  is an empirical constant that is in the order of 2.5 for methane. Substituting this into Eq. 5 and dividing both sides by  $U_o$  results in

$$1 - \frac{dU}{dx} \frac{(x_f - x_o)}{U_o} = \frac{S_L (1 + K u')}{U_o} \quad (6)$$

The similar feature of the  $U/U_o$  profiles means that the normalized axial divergence rate (i.e.,  $(dU/dx)/U_o$ ) has a constant value ( $\approx 8 \text{ m}^{-1}$  from data of Fig 8a). On the right hand side,  $(1 + K u')/U_o$  tends to a constant value for large  $u'$ . This is because the turbulence at the flame stabilization point is isotropic such that  $u'$  scales linearly with  $U_o$  as expected of turbulence produced by a perforated plate. Therefore, if  $S_L$  is held constant, (i.e., at a fixed  $\phi$ ) the flame position  $x_f$  attains a constant value that is independent of  $U_o$  and  $u'$ . As long as the flow similarity is preserved, the flame can be held at the same  $x_f$  position. Changing  $\phi$  will have an insignificant effect on  $x_f$  because the range of  $S_L$  for  $\text{CH}_4$  air flames (0.2 to 0.5 m/s) is small compared to the other values and constants in Eq (6). This analysis also shows that the turbulent flame speed  $S_T$  is the important combustion parameter to consider when adapting the LSC for different fuels.

However, measurements and predictions of  $S_T$  are still active areas of fundamental research and data for the type of fuels IGCC turbines utilize are unavailable. But a lack of scientific  $S_T$  data does not present a significant technical hurdle because the LSI developed for natural gas can be the benchmark to be adjusted for the slower and faster burning syngases. From Eq. (6) it can be seen that faster burning gases (e.g., high  $\text{H}_2$  constituents) need a lower divergence rate. Conversely, the slower burning gases (e.g., highly diluted syngas) need higher divergence rates. Of course, there are other combustion characteristics such as heat release ratios and preferential diffusion of the fuel components (e.g. between  $\text{H}_2$  and  $\text{CH}_4$ ) that need to be considered. From our studies of methane, ethylene, propane, and hydrogen flames, contributions from these other factors tend to be of secondary nature.



### 3.2.1.4.2-5 Development of low-swirl injectors for natural gas turbines

To adapt low-swirl combustion for gas turbines the most pressing question is whether or not this flame stabilization method is operable at elevated temperatures and pressures. To seek an answer, a jet-LSB of  $R_b = 3.8$  cm was constructed for proof-of-concept test at Solar Turbines, San Diego. Successful firing of this LSB at typical gas turbine combustor inlet temperatures (220 and 341°C), pressures (5 and 10 atm), and loads (0.6 to 1.2 kg/s air) showed the concept to be valid. Light-off of the LSB was easy even at elevated temperatures and pressures. The flame remained very stable and free of unacceptable pressure fluctuations towards lean blow-off. The trends of the jet-LSB emissions were also typical of other DLN injectors but the overall concentrations of  $\text{NO}_x$  and CO were higher. This was caused by the poor mixing from a rudimentary fuel spoke injector and significant dilution from the nitrogen swirl jets.

Following the proof-of-concept tests the next logical step was to design and evaluate a vane LSI prototype. The lack of relevant background knowledge on low-swirl flows and turbulent flame speeds at gas turbine conditions remained the main obstacle. To circumvent this difficulty and reduce engineering design efforts and prototype fabrication costs, a decision was made to pursue a fast-track developmental path which exploited, as much as possible, the current injector hardware parts. Because the annulus swirler is the main component of Solar Turbines' SoLoNO<sub>x</sub> Taurus 70 high-swirl injectors (HSI), the preferred option was to investigate if the HSI swirler could be converted to operate in the low-swirl mode.

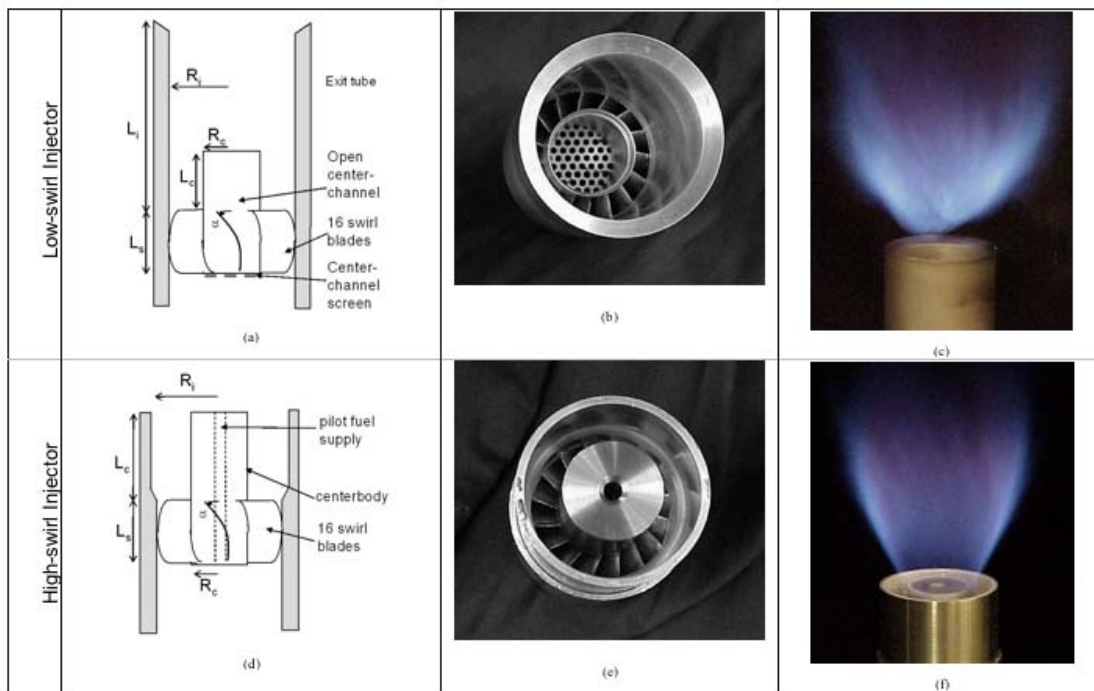


Fig. 9. Schematics and photographs of the LSI (top a-c) and the HSI (bottom d-f)

The LSI (Fig. 9 a-c) converted from the HSI (Fig. 9 (e-f)) has the same basic configuration as the LSB. The SoLoNO<sub>x</sub> swirler (Fig. 9c) has a modular design such that the solid centerbody can be easily removed to form the center-channel for the LSI (Fig 9b). Thus, the two key parameters of the LSI,  $\alpha$  (40°) and  $R$  (0.63), are fixed by SoLoNO<sub>x</sub> swirler having an outer radius of 3.27 cm and a centerbody radius of 2.06 cm with 16 aerodynamically shaped curved vanes. To configure the other LSI parameters,  $S$  and  $L$ , the guidelines for atmospheric LSB were followed. The swirler recess of  $L = 9.5$  cm satisfies the  $2 < L/R_b < 3$  criterion. The swirl number,  $S$ , was set between 0.4 and 0.55 by the use of center channel screens with blockage of 50 to 73%. These screens were fitted to the LSI and tested at laboratory conditions with  $\text{CH}_4/\text{air}$  mixtures at a range of stoichiometry and a fixed bulk flow velocity,  $U_0 = 5$  m/s ( $\approx 35$  kW). The optimum was a 58% blockage screen that stabilized the flame at 1.5 to 2.5 cm downstream of the injector exit. From effective area measurements,  $m$  for this LSI was 0.3, thus 23% of the reactants passed through the center channel unswirled. This gave a swirl number  $S$  of 0.5 for the LSI. In comparison, the swirl number determined for the HSI was 0.73. Even though the difference in  $S$  between LSI and HSI is slight, figure 9f shows that the HSI flame is attached to the centerbody while the LSI flame of figure 9c is detached.

### 3.2.1.4.2 Low Swirl Combustion

The flowfields of the LSI and the HSI flames were also investigated by PIV<sup>9</sup>. Figure 10 shows the results obtained for CH<sub>4</sub>/air flames with  $\phi = 0.8$  at 87 kW. Under these conditions, the bulk velocities for the LSI and HSI were 9.6 and 12 m/s respectively. To illustrate the differences between the flowfields of the two injectors, streamlines have been traced from the velocity vectors. For the LSI, its flowfield features are essentially the same as those of the LSB of figure 3. The spreading of the streamlines near the bottom corresponds to the divergent flow and their slight bends through the flame brush are associated with heat release effects. Downstream of the flame brush, the streamlines are relatively parallel showing a uniform flow of the hot products. The color flooded contours of the shear stresses in the background illustrate again that the flame does not experience high stresses.

In contrast, the flowfield of the LSI is characterized by several high shear regions with the flame zones encountering the highest stress levels. These large velocity fluctuations with very steep instantaneous local gradients make the flame vulnerable to stress-induced non-uniform heat releases as well as local flame extinctions. Downstream of the flame, strong recirculation is shown by the streamlines forming into two separate loops. This is the crucial flow structure for HSI that provides a steady source of hot products for igniting the incoming reactants and holding the propagating flame. The PIV results clearly show that HSI flowfields are dominated by very large velocity gradients and vortex structures. With the LSI flowfield showing more uniformity, the flame characteristics and behavior produced by the two injectors are fundamentally different.

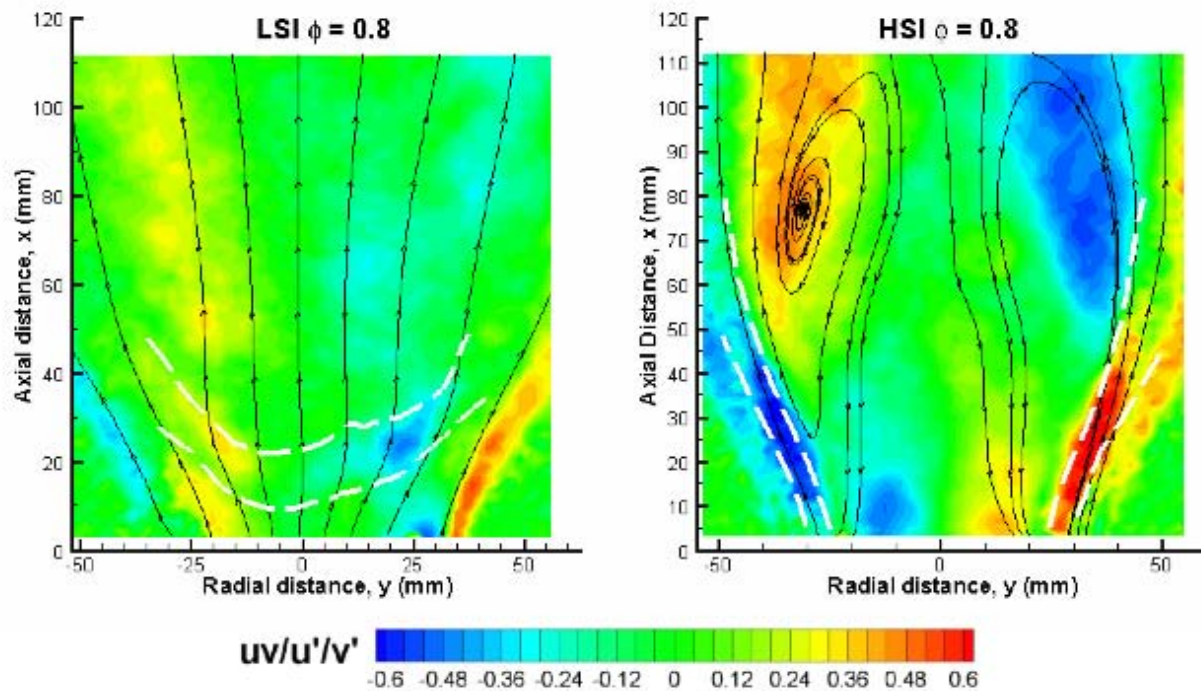


Fig. 10. Streamlines and shear stresses of HSI and LSI burner CH<sub>4</sub>/air flames at  $\phi = 0.8$  and 87 kW. The turbulent flame brushes are outlined by the white dash lines.

Subsequent to the laboratory tests, the LSI was evaluated to determine its operability at gas turbine conditions as well as its effectiveness in lowering emissions. The first set of tests was performed with preheated air at atmospheric pressure to observe flame positions, flame shift with  $U_0$ , and sensitivity to mixture homogeneity. Visual observation during these tests showed that the locations of the flames were not highly sensitive to  $U_0$ ,  $\phi$  and initial temperature  $T_0$ . Flashback did not occur throughout the test matrix. The flame size was similar to that of the HSI flame indicating that the LSI can use the same combustor liner. Tests performed with two premixers with +/- 3% and +/- 10% mixture uniformity showed no effects on NO<sub>x</sub> emissions, overall flame behavior and flame characteristics.

Next the LSI was fitted to a standard film-cooled combustor liner and tested in a high pressure combustion rig. The combustor rig-test matrix covering  $T_0$  of 360 to 430°C,  $P_0$  of 5 to 15 atm and air flow of 0.4 to 1.33 kg/s represented the partial and full load conditions of Solar Turbines' SoLoNO<sub>x</sub> engines of 5 to 7 MW. Successful firing of the LSI at these conditions showed that its operating range is fully compatible with that of the HSI. Throughout these tests, there were no indications of shifting in flame positions or flashback. Excessive acoustic amplitudes were not observed and peak rms acoustics pressures were generally below the allowable 3.4 kPa established for production hardware. Figure 11 shows NO<sub>x</sub> and CO emissions from the LSI (corrected to 15% O<sub>2</sub>) compared with the emissions of HSI. Due to the variation in  $T_0$  and  $P_0$ , the combustion temperature was not proportional to  $\phi$ . Instead, the emission data was plotted against the theoretical adiabatic flame temperature  $T_{ad}$  (for the combustor-rig  $T_{ad}$  was calculated for the primary zone). As can be seen, all the NO<sub>x</sub> emissions from LSI collapsed onto a consistent trend that crossed the 5 ppm threshold at  $T_{ad} < 1920$ K. The strong correlation of NO<sub>x</sub> emissions with  $T_{ad}$  showed that thermal NO<sub>x</sub> was the predominant reaction pathway. In comparison, NO<sub>x</sub> emissions of HSI were generally higher and only approached the 5 ppm NO<sub>x</sub> threshold before LBO. The over 2.5 times NO<sub>x</sub> emissions reduction offered by LSI represents a significant improvement of DLN technology. Moreover, these results imply that the LSI can operate farther away from LBO (higher  $T_{ad}$ ) where it is less prone to combustion oscillation. Although the CO emissions in figure 8b do not show a consistent trend, all but one point from the high  $T_0$  and  $P_0$  runs is below 5 ppm. Therefore, the LSI does not entail compromising CO for the sake of lowering NO<sub>x</sub>.

The emissions from LSI rig-tests are very encouraging and show that the LSI has the potential to bring about a substantial reduction in NO<sub>x</sub> emissions from DLN gas turbines without incurring significant add-on cost or system complexity. The lowest NO<sub>x</sub> emission of < 2 ppm (at 15% O<sub>2</sub>) is comparable with those from the more costly and much less durable catalytic combustor. Despite the complexity of the NO<sub>x</sub> formation mechanisms, the flowfield characteristics of LSI may provide an explanation for why it is highly effective in reducing NO<sub>x</sub>. Recent studies of high-swirl combustion have shown a correlation between NO<sub>x</sub> emissions and the residence time within the recirculation zone. Trapped by the recirculation vortex, a portion of the combustion products resides for a prolonged period at high temperature, which allows the NO<sub>x</sub> formation mechanism to continue and increase in concentrations. The PIV results show clearly that the LSI does not have a recirculation zone to trap a large recirculating mass, therefore, the residence time of the hot products in a LSI is much shorter than in a HSI and truncates NO<sub>x</sub> formation in the post flame region.

Continuing the effort to develop the LSI for SoLoNO<sub>x</sub> turbines, additional tests were conducted to show that the emissions and flame stability of LSI are not highly sensitive to mixture inhomogeneity. Its design can easily incorporate components needed for normal engine operations, e.g., plenum, liner, ignitor, pilot, and pre-mixer. Therefore, adaptation of LSI to current engines does not require significant hardware modifications or change in control strategy or protocol. Currently, an engine-ready LSI prototype has been designed and has undergone a series of single-injector rig tests to verify its readiness for start up, shutdown, load change and offload. It uses the production swirlers made for Solar Turbine's Taurus 70 engines integrated with a pilot and a multi-spokes fuel injector similar to the kind used in current HSIs. The prototype LSIs have been designed to be backward-compatible as "drop-in" replacements for the current HSIs.

### 3.2.1.4.2-6 Development of LSI for IGCC

The development of LSI for natural gas turbines shows that laboratory research is directly applicable to engineering of the turbine hardware. This process is efficient and cost effective and does not require extensive computational fluid dynamics efforts. The same approach is being taken to adapt the LSI concept for IGCC turbines. Currently, progress has been limited to proof-of-concept laboratory demonstration of LSI burning hydrogen and hydrogen/hydrocarbon blended fuels. Much more extensive laboratory studies will be necessary to obtain better understanding of the properties of the various syngas flames to configure the LSI to accommodate the changes in the reactivity, diffusivity and exothermicity. The laboratory studies will also be used for developing scaling rules and engineering guidelines that can be applied to IGCC gas turbines of different sizes.

Due to the different constituencies and concentrations of the two principal types of gasified coal fuels, accommodating the variability in fuel properties is the main challenge in adapting the LSC technology for IGCC turbines. From oxygen-blown coal gasification, typical compositions of the syngas are 25% H<sub>2</sub>, 40% CO, 20% H<sub>2</sub>O. This fuel has a lower heating value of only 8.3 MJ/m<sup>3</sup> compared to 42 MJ/m<sup>3</sup> for natural gas. Due to the high level of dilution, the flame speeds of this syngas are much lower than those of natural gas and they also burn at lower flame temperatures. The key design issue is to stabilize these weak and not highly flammable flames without affecting engine operability. Mitigating NO<sub>x</sub> emissions will not be a significant challenge due to the lowered flame

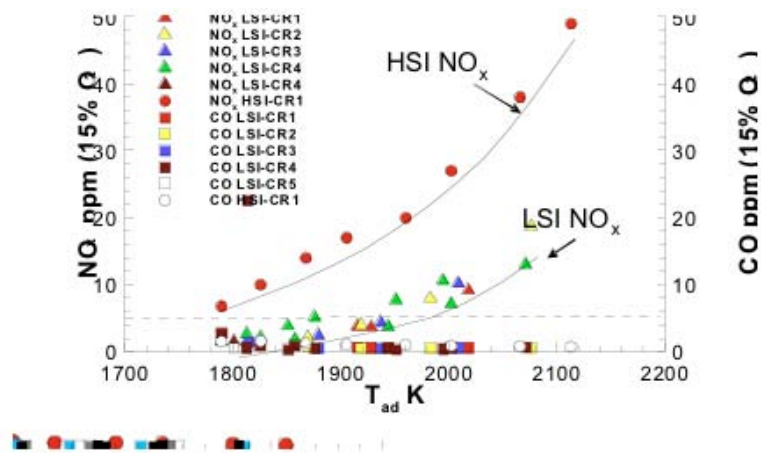


Fig. 11. NO<sub>x</sub> and CO emissions of natural gas LSI and HSI from rig-tests at 5 <  $P_0$  < 15 atm and 360C <  $T_0$  < 430°C.



### 3.2.1.4.2 Low Swirl Combustion

temperatures. The second type of syngas is produced with  $\text{CO}_2$  separation and sequestration to change the compositions to mostly hydrogen at 65-85%  $\text{H}_2$ , 15-35%  $\text{H}_2\text{O}$ . This syngas is much more flammable with flame speeds several times higher than natural if it is not diluted by  $\text{N}_2$  from the air separation unit. The basic issues for LSI development are now shifted to stabilizing these potentially faster flames at very lean conditions where the flame temperatures are sufficiently low to prevent  $\text{NO}_x$  formations. Additional issues arise due to the high diffusivity of  $\text{H}_2$  and its low flammability limit. Moreover,  $\text{H}_2$  rich mixtures have shorter auto-ignition delays than hydrocarbon mixtures. Therefore, integration of the LSI with fuel injection and premixer will be a significant part of the development.

To gain insights on some of these issues, a study was performed with a LSB of  $R_b = 2.54$  cm,  $R = 0.6$  by burning blended mixtures of laboratory grade  $\text{CH}_4$  and  $\text{H}_2$  with concentrations progressively varied from pure  $\text{CH}_4$  to pure  $\text{H}_2$ . The test conditions were the same ( $U_0 = 10$  m/s) as the conditions for the original laboratory experiments performed to develop the natural gas LSI. While this LSB was found to burn pure  $\text{H}_2$ -air flames, a limiting flame phenomenon was found. Shown in figure 12 is the flame stabilization map obtained for the  $\text{CH}_4$ - $\text{H}_2$  mixtures consisting of the (LBO) limit as well as an additional limit where partially rim-attached flames were observed. The LBO limit is the boundary between the blowoff region and the stable lifted flame region. It has a decreasing trend towards lower  $\phi$  values with increasing  $\text{H}_2$ . This is consistent with increasing flammability due to the presence of  $\text{H}_2$ . However, for a mixture with more than 20%  $\text{H}_2$ , the flames transition from fully-lifted flames to partially rim-attached flames when  $\phi$  is increased. The attached flame indicates that the mixing layer between the swirling reactants and the surrounding air has become flammable. This is caused by  $\text{H}_2$  diffusing preferentially into the surrounding ambient air when the overall fuel concentration increases with  $\phi$ . A partially attached flame is a consequence of the tail end of the lifted flame curled back upstream to ignite the mixing zones. While this phenomenon does not seem to affect the flame at the center region, it alters the overall flowfield dynamics and how the flame behaves within a combustor. The limit for partially attached flames also showed a decreasing trend with increasing  $\text{H}_2$  and thus the range of conditions for pure  $\text{H}_2$  flames was very small. This phenomenon showed that the highly diffusive nature of  $\text{H}_2$  needs to be carefully considered in the design of LSI for syngases.

At test condition of  $U_0 = 10$  m/s, the 100%  $\text{H}_2$  flames are close to the flashback point. This is because of the high laminar flame speeds compared to those of methane. In accord with Eq. (6), the faster burning  $\text{H}_2$  flames also sit closer to the burner exit. The close proximity of the  $\text{H}_2$  flames can be one of the contributing factors for the onset of partial flame attachment. Therefore, to modify the current natural gas LSB for syngases with high  $\text{H}_2$  constituency, the flame needs to be maintained at a position further downstream. This can be accomplished by relaxing the normalized divergence rate  $(dU/dx)/U_0$  through lowering of the swirl number  $S$ . Conversely, for syngases with low heating values, the current LSB will generate flames that are further downstream and this is not optimum. To draw these flames closer to the burner exit, it would be necessary to increase the normalized divergence rate by increasing  $S$ . This illustrates that the flame speed is the important parameter for engineering the LSI for different fuels.

Consequently, adjusting the LSI swirl number for each fuel is the first step toward development for IGCC turbines. Using the natural gas LSI as a benchmark, the strategy is to determine the  $S$  range for different fuels with various dilution levels. The results will be analyzed to obtain operating maps expressed in terms of  $S$ ,  $T_{ad}$ , and  $\phi$ . Using the flame temperature and  $\text{NO}_x$  emissions as the reference parameters, these maps will guide the development of fuel-flexible LSI prototypes that can accommodate several fuel types. Refinement of the designs to further optimize for differences in combustion characteristics such as exothermicity, preferential diffusion of the fuel components (e.g., between  $\text{H}_2$  and  $\text{CH}_4$ ) and other non-linear behavior can be accomplished through further rig tests with preheated air and at simulated gas turbine conditions.

As LSI technology is still under development, issues concerning its full integration to gas turbine engines are still being investigated. The significant outstanding issue is, of course, the combustion oscillation characteristics of the LSI. The interesting question from both the scientific and technological perspectives is whether or not the absence of a large recirculation zone in the LSI flame will have an influence on the combustion oscillation characteristics. From field tests of atmospheric boiler and furnaces, the LSBs show relatively low tendencies to incite combustion oscillations. Rig-tests of the LSI at simulated gas turbine conditions also indicate the absence of a strong characteristic acoustic signature from the flame. Though these observations are encouraging, the combustion oscillation characteristics of LSB and LSI need to be investigated more systematically to gain a fundamental understanding for addressing issues that may arise when the technology is adapted for more complex systems such as IGCC gas turbines.

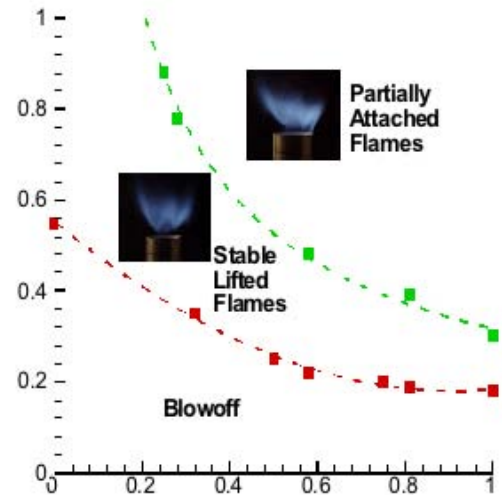


Fig. 12. Stability limits of a  $R_b = 2.54$  cm,  $R = 0.6$  LSB for  $\text{CH}_4$ - $\text{H}_2$ -air flames at  $U_0 = 10$  m/s.

### 3.2.1.4.2-7 Conclusions

Low-swirl combustion (LSC) is a very promising simple, robust, and cost-effective solution to attain single-digit  $\text{NO}_x$  operation. Already commercialized for industrial process heaters and currently being adapted for natural gas turbines, development of LSC for IGCC turbines can provide a simple and direct solution to resolve important complex coupling issues concerning fuel-variability, reliability, and emissions. LSC exploits a patented combustion aerodynamic process to burn ultra-lean premixed turbulent flames that emit very low levels of  $\text{NO}_x$ . Originally developed for basic research, a good understanding of its operating principle has been obtained. The principle is fundamentally different than the high-swirl method used in all current DLN engines. Instead of relying on a very high level of swirl to generate a well formed vortex to “hold” the flame, LSC takes the opposite approach. By lowering the swirl intensity until a recirculation zone is not formed, it generates a divergent flow with a non-swirling center flow region. Linear velocity decay within the center region provides a stable flow configuration where the premixed flame freely propagates and maintains itself at the position where the local flow velocity is equal and opposite to the turbulent flame speed. Flash back is prevented because the flame cannot propagate faster than the velocity upstream. Blow-off is mitigated because the center flow region provides a broad range of velocities where the flame naturally re-settles during occasional swings in flow or mixture conditions.

For practical implementations, the scientific background of LSC provides a sound foundation for the development of a patented vane swirler. It consists of an annulus swirl vane section found in many other swirler designs but with an open center channel that allows a portion of the reactants to remain unswirled. Laboratory experiments, prototype development and testing, and extensive analysis of the flow and emission data have produced a set of scaling rules and engineering guidelines that have been applied successfully to develop and commercialize low-swirl burners (LSB) of 17 kW to 7.5 MW for meeting ultra-low emission goals of  $< 7$  ppm  $\text{NO}_x$  and CO at 5%  $\text{O}_2$ . Central to the rules and guidelines is a new definition of the swirl number based on the geometric variables that include the vane angle, ratio of the center channel radius to burner radius, swirler recess, and the flow split between the center core and swirled flow. By setting specific ranges for the swirl number and for the geometric variables, LSB can be configured to meet emissions goals as well as system integration, performance, and operational requirements. These rules and guidelines have also been applied to develop low-swirl injectors (LSI) for 5 to 7 MW gas turbine engines. To be compatible with existing engines, the LSI prototypes were made using the key components engineered for current production high-swirl injectors. Single injector rig-tests of the LSI prototypes showed them to emit  $< 5$  ppm  $\text{NO}_x$  and CO at 15%  $\text{O}_2$  at simulated part-load and full-load conditions. This represents a 2.5 times emissions reduction compared to current DLN high-swirl combustion technology. These results also showed that atmospheric laboratory experiments are directly applicable for designing and engineering of gas turbine hardware. Upon the completion of the single injector rig-tests, a set of pre-production LSI prototypes is being fabricated for engine tests in late 2006. These prototypes have been designed to utilize many key components from current production DLN high-swirl injectors and configured to be “drop-in” replacements for existing engines. Due to the robust low-swirl combustion mechanism, the operability of the engine such as lightoff, shutdown, off load, and load change are not expected to be affected when the new LSI are used. From system integration and cost standpoints, the most significant feature of both the LSBs and LSIs is that they can be fully compatible with current systems using some of the same components (i.e., plenum, swirler, air compressors, blowers, premixer, pilots and ignitor) but with significant performance improvements in terms of emissions, turndown, and stability.

The laboratory studies also provide the scientific insights necessary for adapting the technology to accept different gaseous fuels. Measurements of the velocity distributions and turbulence statistics have shown that low-swirl produces self-similar flowfields that scale linearly with bulk velocities (i.e., input power). Because premixed turbulent flames propagate at turbulent flame speeds that also scale linearly with the turbulence intensity and bulk flow velocity, the flow and flame features are coupled optimally to give LSC its exceptional performances. Therefore, the adaptation of LSC to different IGCC syngases involves primarily the adjustment of the LSC flowfield via the swirl intensity and other geometric variables to accommodate for the changes in the flame speeds. Proof-of-concept laboratory experiments have already been performed and have shown that LSC can burn pure  $\text{H}_2$ /air flames. The plan towards further development for IGCC includes experimental measurements of the flame speeds for syngases and developing guidelines for fuel-flexible LSIs.

### 3.2.1.4.2-8 Notes

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